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# Best Available Technology for P-Recycling from Sewage Sludge—An Overview of Sewage Sludge Composting in Austria

**Bernhard Stürmer [1,*] and Melanie Waltner [2]**

1 Institute for Management, Research and Innovation, University College of Agrarian and Environmental Education, 1130 Vienna, Austria
2 Austrian Compost and Biogas Association, 1010 Vienna, Austria; waltner@kompost-biogas.info
* Correspondence: bernhard.stuermer@haup.ac.at; Tel.: +43-664-30-40-758

**Abstract:** In order to close the phosphorus cycle in the long term, efficient recycling processes are necessary to ensure that this critical nutrient can be returned to arable land. Sewage sludge recycling is of particular importance due to the relatively high phosphorus content of sewage sludge. In this article, the current recycling paths of Austrian sewage sludge are highlighted, focusing on the advantages and limitations of sewage sludge composting. In addition to nutrient contents, pollutant loads were also analyzed in order to also discuss the limitations of this recycling pathway. Therefore, data from Austrian composting plants with focus on sewage sludge are used. The results show that the currently relevant pollutants (heavy metals) are predominantly below the limits prescribed for recycling and spreading on arable land. However, in order to decide on a recycling path at an early stage, a pollutant monitoring system must be in place. Due to pollution, mono-incineration with subsequent phosphorus recovery is also currently being discussed in Austria. Mono-incineration can represent an important component of sewage sludge disposal, because some sewage sludges are not suitable for composting due to potential environmental hazards. Therefore, it is important that evidence-based limit values and measures for the reduction in pollutants for input sources are determined.

**Keywords:** composting; recycling; sewage sludge



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## 1. Introduction

Every year, more than 40 million tons of phosphate are used worldwide as mineral fertilizer in agriculture. After nitrogen, phosphate is the most important nutrient, in terms of quantity, for maintaining soil fertility and increasing agricultural production [1]. EU-wide, phosphorus consumption in agriculture has decreased only slightly compared to the year 2000, and the use of elemental phosphorus remains at a high level (around 1.2 million tons) [2].

Due to phosphorus leakage throughout the entire food processing chain, concerns have been raised regarding future phosphorus supply on the one hand, and the corresponding water contamination on the other [3,4]. Another area of concern is the unequal worldwide distribution of phosphorus reserves. The EU only has low reserves of phosphate-bearing rock, and thus relies on imports, with Morocco and Kazakhstan among its main import countries [5]. Moreover, prices have fluctuated notably during the past few years. In order to close the phosphorus cycle in the long term, efficient extraction, utilization and recycling are necessary. Due the increasing demand for fertilizers, security of supply and an even regional and worldwide distribution of phosphorus must be ensured [6,7]. The European Commission has also recognized this, and lists phosphor and phosphorite as critical raw materials [8].

Due to the relatively high amounts of phosphorus in sewage sludge, recycling is of particular importance [9].

At municipal wastewater treatment plants, phosphorus is recovered through building up the sewage sludge biomass by bacteria (about 30% of P), chemical precipitation using iron (Fe) and aluminum (Al) salts, and through increased biological phosphorus uptake. Some of the phosphorus bound in the biomass can be recovered by its degradation. The chemically precipitated iron and aluminum phosphate compounds are comparatively stable, and can only be recovered by lowering the pH value of the medium (pH < 5). The common starting points for P recovery are the liquid phases at the wastewater treatment plant, the sewage sludge and the sewage sludge ash [10].

Phosphorus, as well as other nutrients, mainly reach wastewater via food waste, food and feed processing, and therefore ultimately via the agricultural sector. In accordance with the circular economy, phosphorus should be returned to arable land. In Austria, for example, the total amount of phosphorus from municipal sewage sludge is estimated at 6500 t P (14.800 t $P_2O_5$), which corresponds to about one-third of the phosphorus returned to the market via commercial fertilizers [11].

In the EU, the treatment and use of sewage sludge is defined in the Sewage Sludge Directive [12]. This contains limitation values for heavy metals and determines the procedure for heavy metal analyses. The directive aims to enable utilization of the nutrient content of sewage sludge whilst avoiding harmful effects from its use [13]. For example, as pointed out by Kelessidis and Stasinakis [14], a variety of technologies for stabilization, conditioning, dewatering, or other processes are used to treat sewage sludge in the European Union.

This review illustrates the current recycling paths of Austrian sewage sludge. For this purpose, Section 2 analyzes the current sewage sludge volume as well as the two recycling paths that are currently pursued. Section 3 discusses the problem areas of sewage sludge recycling, and Section 4 briefly assesses whether mono-incineration, which is currently also under discussion in Austria, could be an alternative in the future. For this purpose, literature research on the legal framework as well as on the status quo of sewage sludge recycling in Austria was conducted. The legal framework in Austria is primarily set by the sewage sludge directives and the soil protection laws of the individual federal states. Framework conditions for the commercialization of sewage sludge compost are stipulated by the Compost Directive. The databases on the status quo of sewage sludge utilization are derived from reports by the responsible ministry as well as its downstream agencies.

Past and current assessments were supplemented by the author's own studies in the field of sewage sludge and sewage sludge compost. These analyses are based on the analysis of sewage sludge data, which was intended for direct utilization in agriculture (1264 analyses in the period 2008 to 2019). In addition, data from Austrian composting plants that recycle municipal sewage sludge are used. In total, results of 168 analyses of sewage sludge compost in the period 2009 to 2019 were processed. These data were supplemented with data reported to the authorities (especially input quantities) and specific questions posed to compost plant operators in 2021.

## 2. Current Sewage Sludge Quantity and Utilization in Austria

In 2018, 1869 wastewater treatment plants (WWTPs) with a population equivalent of >50 (PE60, consumption of a person of 60 g BOD5 (biochemical oxygen demand for 5 days) per day) were registered in Austria. Of these, 633 WWTPs had a treatment capacity of at least 2000 PE60, with the total expansion capacity exceeding 22 million PE60. The requirements of Directive 91/271/EEC [15] regarding the reductions in carbon (BOD5 99%, COD (Chemical oxygen demand) > 95%), nitrogen (81%), and phosphorus (91%) are met by Austrian WWTPs [16].

In total, 237,900 t dry matter (DM) of sewage sludge are produced annually in all municipal WWTPs. Most (99%) of the total amount is attributed to WWTPs with more than 2000 PE60 [16,17]. This corresponds to an average of 11 kg DM/PE60/a, with sewage sludge production varying by province (between 7.3 in Styria and 16.8 kg DM/PE60 in

Vienna). As shown in Figure 1, 80% of the sewage sludge originates from the 120 largest WWTPs.

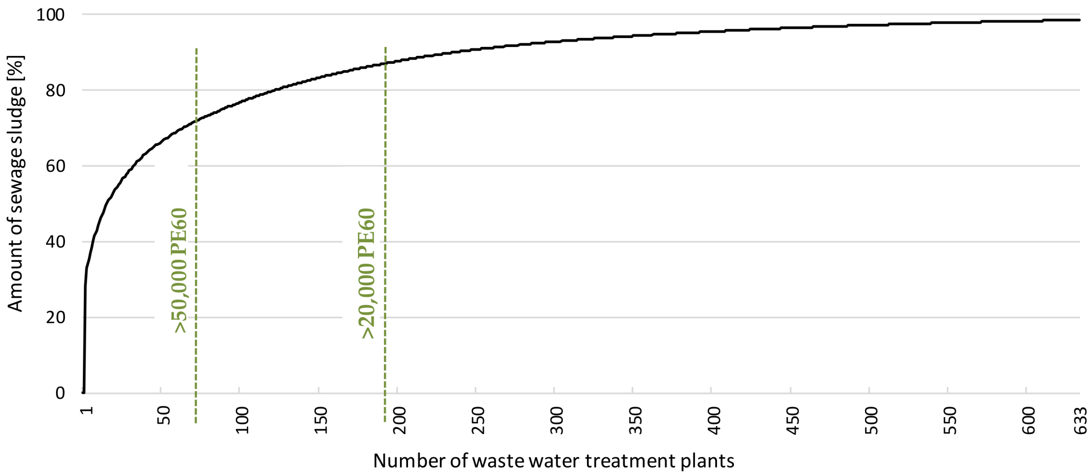


**Figure 1.** Ratio between the number of WWTPs (size sorted in descending order) and sewage sludge volume (100% = 237,900 t DM) (own representation based on [9]).

Currently, almost 50% of sewage sludge (mostly after dewatering) is utilized in agriculture, either via direct spreading or via composting. Slightly over 50% is currently not recycled, but thermally utilized in waste incineration plants and cement plants [10].

### *2.1. Direct Use in Agriculture*

The direct use of sewage sludge allows for the extensive agricultural utilization of the nutrients it contains, whilst avoiding danger to soil fertility and the environment if used as intended. In Austria, the agricultural use of sewage sludge must comply with the soil protection regulations of the respective federal state. For example, in Lower Austria, the utilization of sewage sludge is regulated by the Lower Austrian Soil Protection Act [18] and by the Lower Austrian Sewage Sludge Directive [19]. Only sewage sludge of quality classes I and II (uncritical with regard to heavy metal content, cf. Table 1) is permitted to be applied to Lower Austrian soils. In addition, the nutrient content of the soil and the nutrient requirements of the subsequent crops must be taken into account when determining the quantity to be applied.

**Table 1.** Accepted limits for sewage sludge for the direct spreading on soil according to the Lower Austrian Sewage Sludge Directive [19].

| Heavy Metals | Quality Class I | Quality Class II |
|---|---|---|
| Zinc (Zn) | Lower than the average regional topsoil contents (arable soil up to 25 cm depth, grass land up to 10 cm) | 1500 mg/kg DM |
| Copper (Cu) | | 300 mg/kg DM |
| Chrome (Cr) | | 70 mg/kg DM |
| Lead (Pb) | | 100 mg/kg DM |
| Nickel (Ni) | | 60 mg/kg DM |
| Cadmium (Cd) | | 2 mg/kg DM |
| Mercury (Hg) | | 2 mg/kg DM |
| Chlorinated organics | | 500 mg/kg DM |

Up to around 20% of sewage sludge is spread directly on arable land, both in its liquid and in a pre-treated state. Although the dry matter content of liquid sewage sludge generally amounts to a maximum of 5%, the dry matter content rises to 15% to 45% after pre-treatment (Figure 2). Sewage sludge in Austria is mainly flocculated and centrifuged using polymers [14,20], although solar drying is also used occasionally [21,22]. Humification [23,24] is only common in small WWTPs, but insignificant for the overall volume of sewage sludge.

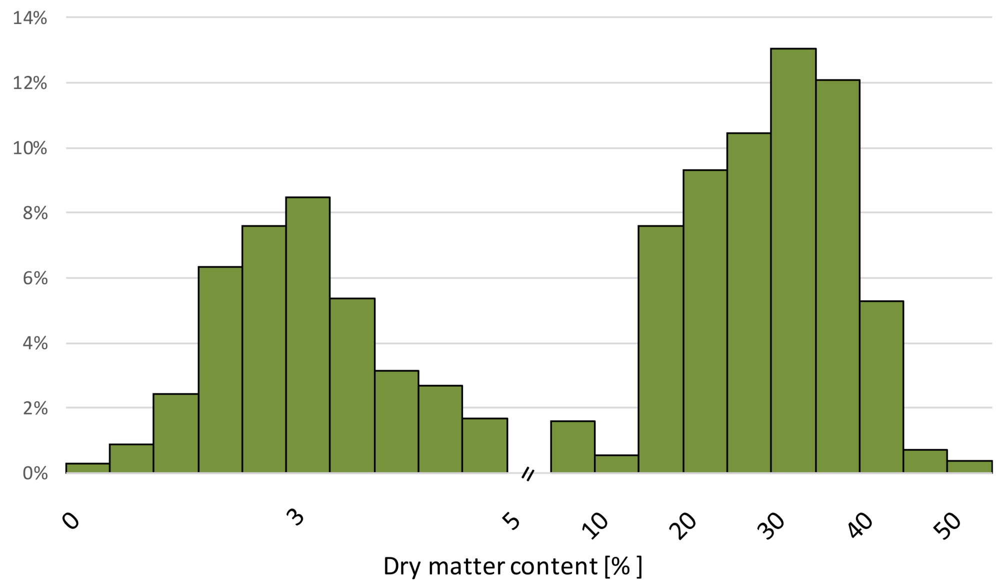


**Figure 2.** Frequency distribution of dry matter content (*n* = 1264) of sewage sludges for direct use on arable and grass land (*y*-axis—frequency of sewage sludge analyses; *x*-axis—dry matter content in percentage).

The main reason for the direct utilization of sewage sludge is the cost-effective import of nutrients for agricultural businesses [6]. Particularly, access to the plant nutrients nitrogen, phosphorus, and potassium, but also to sulfur or lime contained in the sewage sludge, is essential. The amount of sewage sludge currently used directly in agriculture corresponds to a phosphorus quantity of about 1400 t P per year (3000 t $P_2O_5$). Moreover, the carbon input, which is necessary for humus formation and nitrogen mobilization, is also important [25].

The range of nutrient contents of the available analytical values of sewage sludges are shown in Figure 3. On average, the nitrogen content was 0.63% of fresh matter, the phosphorus content ($P_2O_5$) was 0.98% FM, the potassium content ($K_2O$) was 0.05% FM, and the carbon content was 4.84% FM. The C:N ratio averaged as 8.4:1, which was higher than the C:N ratio of digestate [26].

### *2.2. Sewage Sludge Composting*

Currently, around 25% of sewage sludge, corresponding to around 1600 t P (3800 t $P_2O_5$) is utilized "otherwise". This includes mechanical–biological treatment, humification, and especially sewage sludge composting. In order to recycle sewage sludge in composting plants, it is first treated by waste collectors and processors. In cases of sewage sludge composting, water regulations are no longer applicable and waste regulations apply instead. Figure 4 shows the locations of all registered sewage sludge processors.

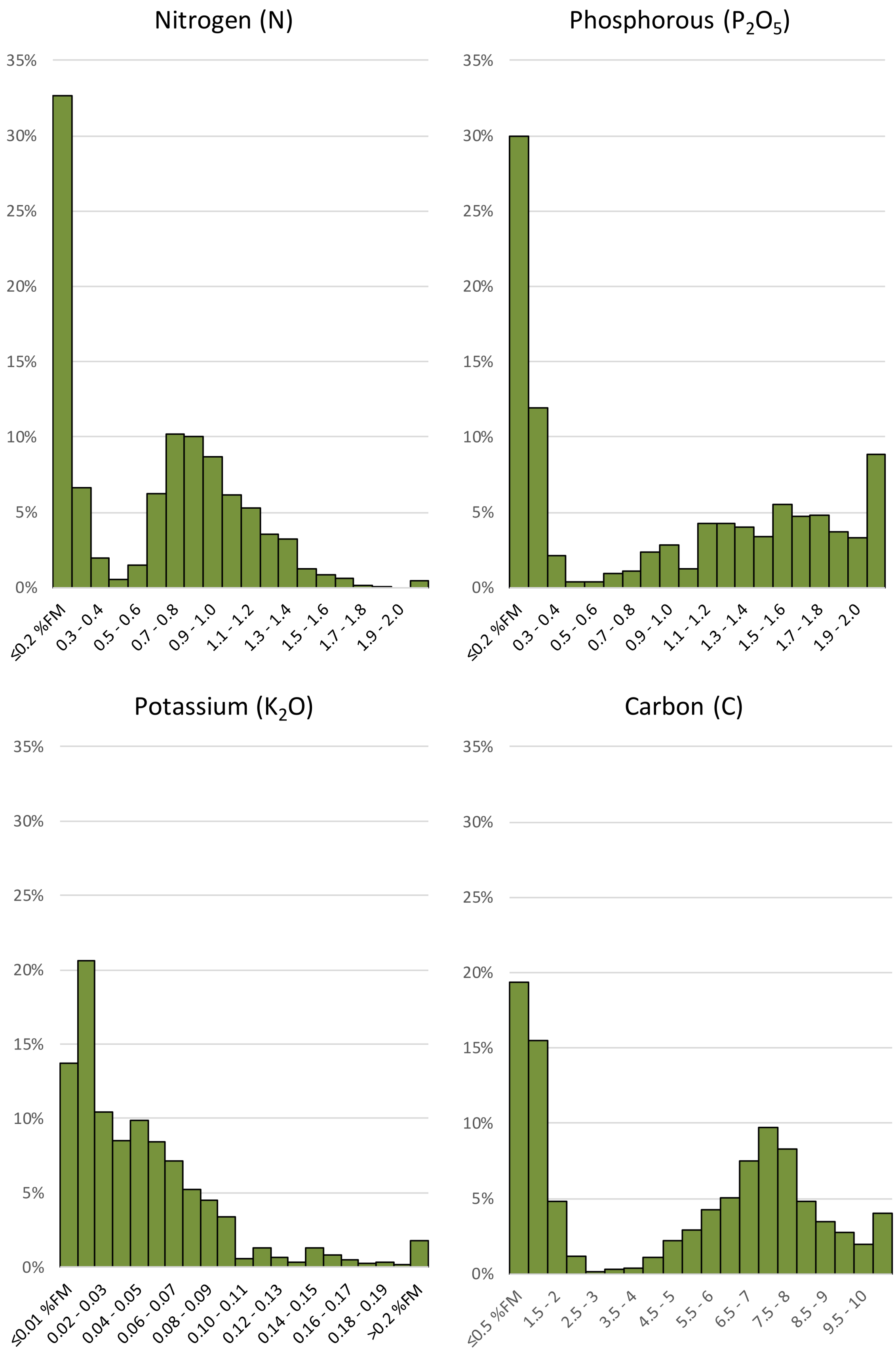


**Figure 3.** Frequency distribution of nitrogen ($n$ = 1257), phosphorus ($n$ = 1180), potassium ($n$ = 1208), and organic carbon ($n$ = 1264) of Austrian sewage sludges ($y$-axis—frequency of compost analyses; $x$-axis—nutrient content of fresh matter in percentages).

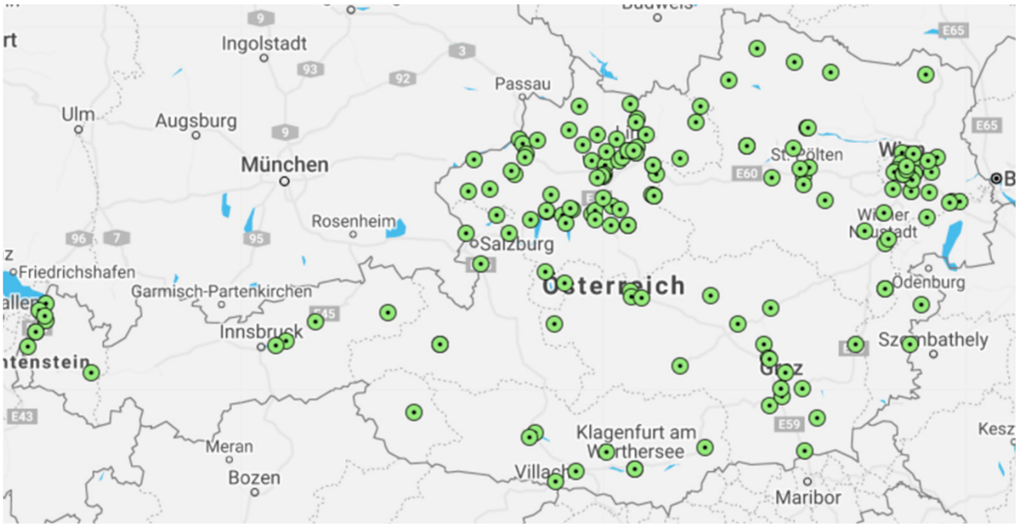


**Figure 4.** Locations of sewage sludge processors in Austria (own presentation based on [27]).

Based on the Waste Catalogue Directive [28], a distinction was made between municipal quality sewage sludge (key number 92201) and municipal sewage sludge (key number 92212), both of which are intended for biological treatment. Biological treatment via composting plants is regulated by the Austrian Compost Directive [29]. The Compost Directive is an end-of-waste type of directive: sewage sludge, which is considered waste, is turned into a product—either quality sewage sludge compost or sewage sludge compost, depending on its heavy metal contents (Table 2). The suitability of the raw materials must be confirmed by a certificate of origin and an analysis.

**Table 2.** Limit values for sewage sludge for the production of (quality) sewage sludge compost [29].

| Heavy Metals | Limit Values for the Production of: | |
|---|---|---|
| | **Quality Sewage Sludge Compost** | **Sewage Sludge Compost** |
| Zinc (Zn) | 1200 mg/kg DM | 2000 mg/kg DM |
| Copper (Cu) | 300 mg/kg DM | 500 mg/kg DM |
| Chrome (Cr) | 70 mg/kg DM | 300 mg/kg DM |
| Lead (Pb) | 100 mg/kg DM | 200 mg/kg DM |
| Nickel (Ni) | 60 mg/kg DM | 100 mg/kg DM |
| Cadmium (Cd) | 2 mg/kg DM | 3 mg/kg DM |
| Mercury (Hg) | 2 mg/kg DM | 5 mg/kg DM |

Quality sewage sludge compost is approved for use in agriculture. Sewage sludge compost may only be used in landscaping, for landscape maintenance, and as recultivation layers on landfills.

Available data from Austrian sewage sludge composting plants show that, currently, municipal quality sewage sludge is almost exclusively being processed, with the aim of making quality sewage sludge compost primarily available as a fertilizer (especially N and P) for agricultural use. In the period 2009 to 2019, 95% of the processed sewage sludge was municipal quality sludge and 5% was municipal sewage sludge, with fluctuations within each year ranging from 86:14 to 98:2. The disposal fees for the transfer of sewage sludge to composting plants are currently around 60 EUR/t of sewage sludge.

Sewage sludge treatment must follow the principles of state-of-the-art composting [30]. For a correct composting process, structural material must be added to the sewage sludge in order to achieve optimal aerobic decomposition and conversion. For this purpose, compost heaps are built in a volume ratio of 1:3 when using straw (one part sewage sludge to three parts straw) and in a volume ratio of 1:2 when using shredded shrub and tree cuttings.

The heaps should not exceed a height of 2.20 m. Higher heaps must be actively ventilated. During the main rotting period, the heaps should be turned several times per week, thus achieving a standard principal rotting period of 8 to 12 weeks. When the temperature in the heaps falls below 40 °C, the post-rotting phase is reached. The height of the heaps should again be lower than 2.20 m. During the post-rotting period, the heaps should ideally be turned every 14 weeks and the moisture content should be checked regularly to support compost maturation.

If the requirements stipulated by the Compost Directive are met, an end-of-waste status can be achieved. Quality sewage sludge compost can be placed on the market as a product. Composting of quality sewage sludge thus offers, on the one hand, a high level of disposal security for the sewage treatment plant operators and, on the other hand, avoids danger to soil fertility and the environment when used as intended.

For farmers, the nutrient contents and the levels of organically bound carbon are essential criteria. Figure 5 shows the frequency distributions for the most important nutrients and for carbon derived from 165 sewage sludge compost samples. On average, nutrient contents were found to be 1.0% FM N, 1.7% FM $P_2O_5$, 0.6% FM $K_2O$, and 12.2% FM C. The average C:N ratio was 13.0:1, which is closer to the optimum for soils [31] than with direct sewage sludge applications. Fertilization using compost has additional advantages over mineral fertilization alone. In particular, the organic matter contained promotes the activity of soil organisms, reduces susceptibility to erosion, has a phytosanitary effect, improves soil passability, and increases the nutrient storage capacity [7].

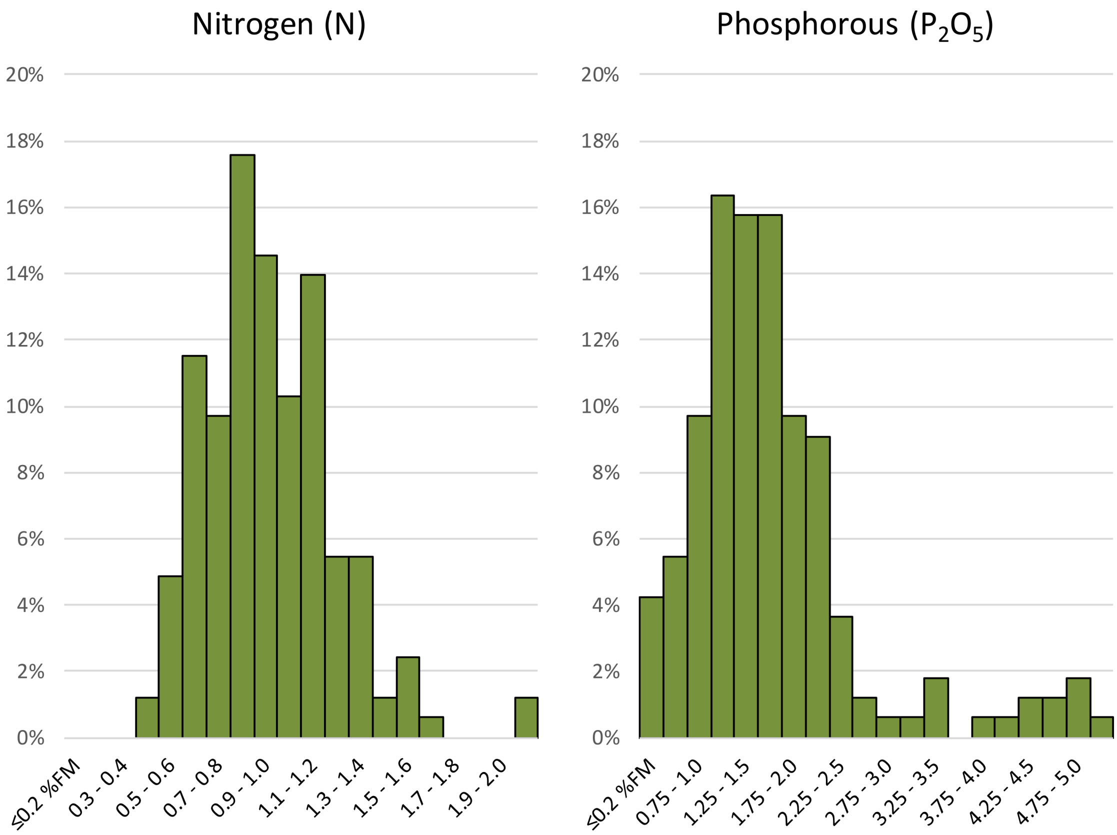


**Figure 5.** *Cont.*

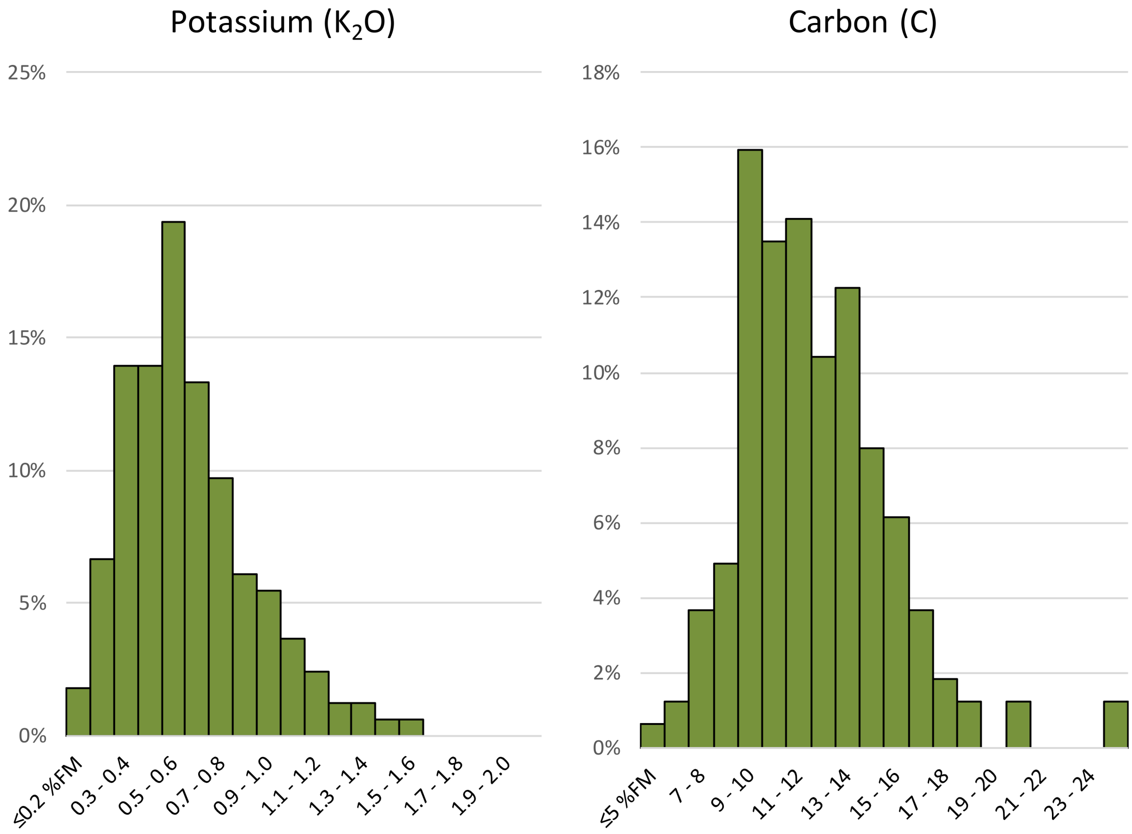


**Figure 5.** Frequency distribution of the contents of nitrogen, phosphorus, potassium, and organic carbon of Austrian sewage sludge composts (*n* =165) (*y*-axis—frequency distribution of compost analyses; *x*-axis—nutrient content of fresh matter in percentages).

## 3. Environmental Impacts of Sewage Sludge

The organic content of sewage sludge has a positive effect on the humus content of the soil. Furthermore, the use of sewage sludge can reduce mineral fertilizer applications. Another advantage results, if the sewage sludge disposal is organized decentral. Shorter transport distances cause lower fuel consumption.

Sewage sludge not only contains plant nutrients such as nitrogen, phosphorus, or potassium, but can also be contaminated with substances such as organic compounds that are difficult to biodegrade, heavy metals, nanomaterials, microplastics, pathogenic microorganisms, or hormonally active agents [32]. If applied to fields, the pollutants can accumulate in the soil, be taken up by plants, enter the groundwater with the leachate, or be directly discharged into water bodies through surface runoff. Therefore, particular attention should be paid to substances that could pose an environmental risk.

### *3.1. Heavy Metals*

Some heavy metals, such as copper and zinc, are essential trace elements for plants, animals, and humans (and are only harmful in higher concentrations), whereas other heavy metals such as lead, cadmium, and mercury are considered pollutants. Input sources of heavy metals include metal sheets used for stormwater drainage systems, abrasion from tires, brake pads, and road surfaces, as well as atmospheric deposition, domestic sewage (including human excreta), and drinking water from the plumbing systems. Geogenic base loads also influence the heavy metal contents of sewage sludge [33].

Considerable heavy metal contamination can also originate from industrial wastewater [33]. The Indirect Conduction Directive [34] was introduced at an early stage to counteract the contamination with undesirable substances. By setting limit values more than 30 years ago, and thus establishing pre-treatment measures for polluters, it was possible to considerably reduce the input of heavy metals in sewage sludge, as Figure 6 shows, using the example of Upper Austria in the years 1979 to 2000. Since 2000, heavy metal concentrations have decreased even further, as shown by the analysis results of the inspections carried out in the province of Upper Austria [35].

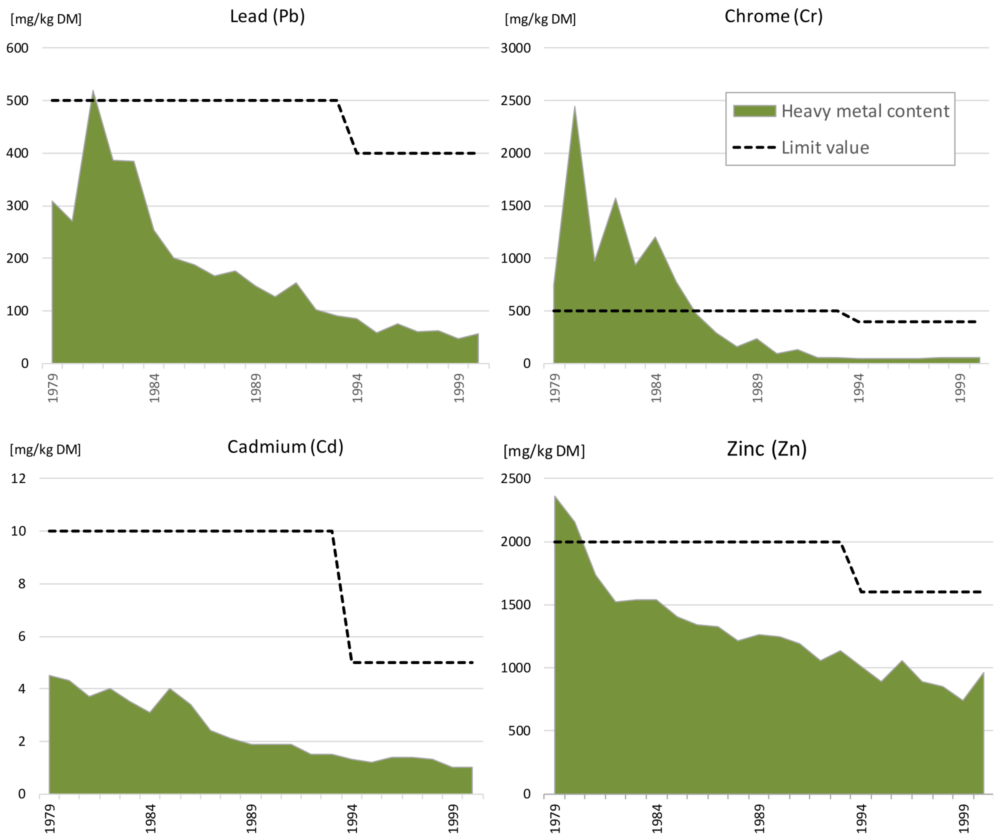


**Figure 6.** Development of selected heavy metal concentrations (Pb, Cr, Cd, and Zn) in Upper Austrian sewage sludge in the period 1979 to 2000 [33].

Heavy metals are not subject to biological degradation, and therefore accumulate in the course of rotting due to mass loss. If the concentrations of heavy metals in the sewage sludge compost exceed that of the soil, accumulation occurs. Therefore, its input into the soil must be kept low. As shown in Figure 7, the heavy metal concentrations in sewage sludge composts are almost exclusively below the legally prescribed values.

### 3.2. Plastics

The Compost Directive [29] distinguishes between three types of extraneous materials: plastics, metals, and glass. Good quality of the input materials is a prerequisite for high compost quality. In sewage sludge composts, the amount of extraneous material is directly dependent on the input material, especially dewatered sewage sludge and structural material (shrub and green cuttings or straw) The amount of extraneous material in sewage sludge compost can be considered low and is below the limit for use in agriculture [36].

Metals and glass hardly cause any problems in sewage sludge composts, whereas plastic inputs need to be critically assessed, as highlighted by public discussions about the impacts of microplastic on the environment [37].

The abrasion of synthetic fibers from textiles, intentionally added microplastics (microbeads) in personal care and hygiene products, abrasions from pipes and seals, and diffuse sources cause inputs of microplastics via household wastewater into the sewer system and further into wastewater treatment plants [37]. Due to the very effective treatment methods of WWTPs, microplastics (mainly fibers) accumulate in the sewage sludge [38].

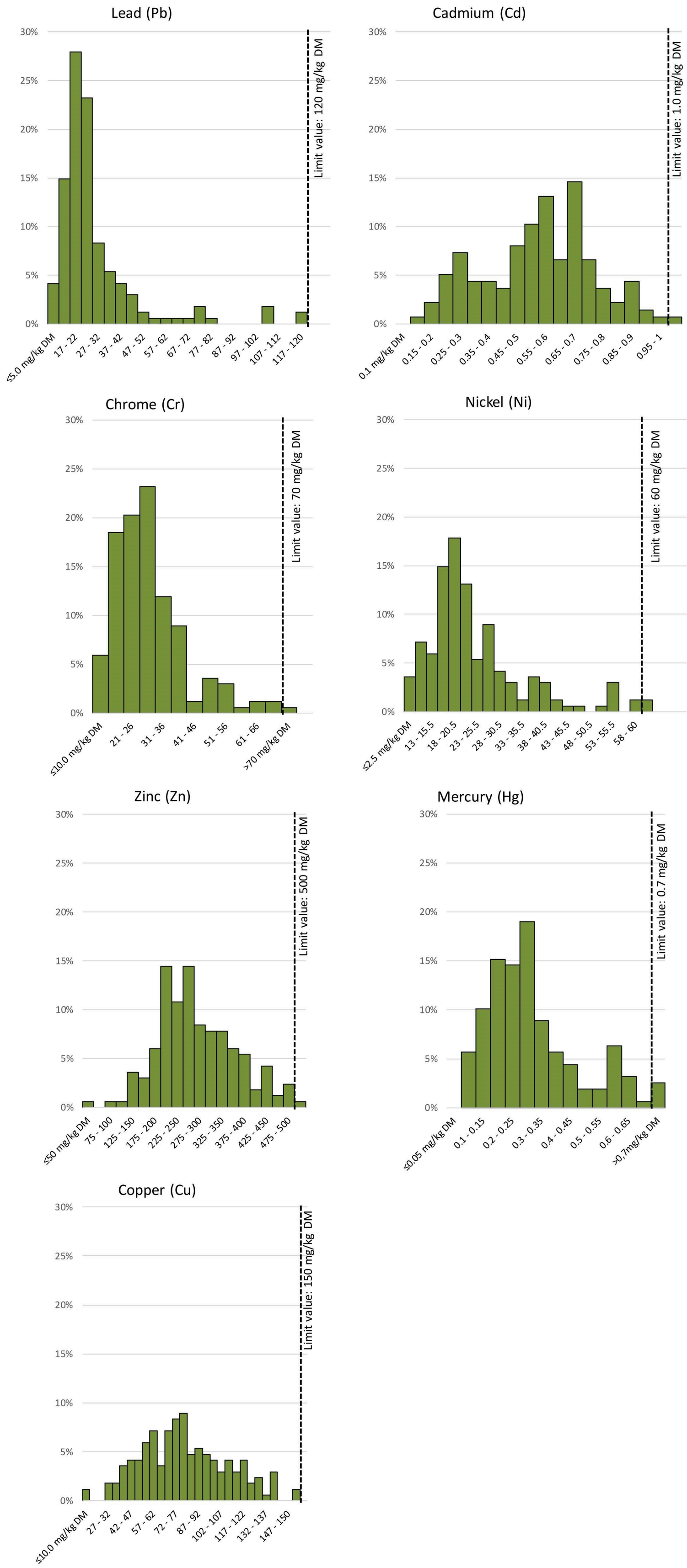


**Figure 7.** Heavy metal concentrations in sewage sludge composts in the period 2009 to 2019 ($n$ =165) ($y$-axis—frequency distribution of compost analyses; $x$-axis—heavy metal content in mg per kg dry matter).

A recent study by Sexlinger et al. [39] investigated polymers in sewage sludge. Polyurethane, polyethylene terephthalate, and polypropylene were found to be the dominant polymer types. Due to the diversity of sources and the ubiquitous use of plastics, an exact attribution of the identified polymer types to potential input pathways is only possible to a limited extent. However, the polymer types predominantly found indicate an input from the above-mentioned sources: polyurethane (PU) is used as a filler for bed linen or as a sealing material; polyethylene terephthalate (PET) is used in the textile and care sectors; and polypropylene (PP) may originate as an abrasive from pipelines or the in use of hygiene products.

Moreover, the study also shows that there is no correlation between the population equivalents and the number of microplastic particles. The amount of microplastics seems to depend mainly on the sewer system or the ratio of private households and industrial dischargers. High levels may, for example, result from dischargers related to the plastics industry, because it is difficult to prevent microplastics from entering wastewater in these processes [39].

The Danish Environmental Protection Agency classifies the number of plastic particles in soils as low (10 mg/kg). Furthermore, hardly any differences in microplastic concentrations were found in soils fertilized with sewage sludge as compared to soils that were not fertilized with sewage sludge [40].

### 3.3. Pharmaceutical Residues

Pharmaceutical ingredients are biologically highly active substances, which interfere with the regulatory mechanisms of organisms. For example, they influence metabolism, shift hormonal balance, or alter cell-to-cell signal transmission. For many pharmaceuticals, long-term studies with a focus on environmental impacts are missing. Moreover, negative effects on flora and fauna are known in some cases. There is also a considerable need for research in connection with antibiotic resistance in bacteria that are human-pathogenic, which are a serious problem in public health. In order to build up a reliable database, the use of pharmaceutics is closely observed, and critical points are monitored [41].

In 1998, for the first time in Austria, the influents and effluents of 11 Austrian municipal wastewater treatment plants, as well as one industrial wastewater treatment plant, were analyzed for selected active pharmaceutical substances. These included the antibiotics penicillin G and V, the sulfonamide Sulfamethoxazole, and its antagonists Trimethoprim and the macrolide Erythromycin.

Due to their instability, neither penicillin G nor V was found. The antibiotics erythromycin (89 to 3020 ng/L), Trimethoprim (<50 to 302 ng/L), and Sulfamethoxazole (up to 234 ng/L) were detected in the effluent of the investigated WWTPs. The antiepileptic drug Carbamazepine was also detected at concentrations ranging from 282 to 1110 ng/L [42].

In 2014, another nationwide investigation was carried out as part of the research project "Monitoring program of pharmaceuticals and wastewater indicators in groundwater and drinking water". Data were collected from 54 groundwater monitoring wells and 50 drinking water monitoring wells, in order to detect selected antibiotics, pharmaceuticals and wastewater indicators in groundwater and drinking water. The active substance Carbamazepine was detected in about 25% of the monitoring sites, with maximum concentrations of 120 ng/L in groundwater and 17 ng/L in drinking water. Erythromycin was not detectable in drinking water; in groundwater, the antibiotic was quantified once at 1.2 ng/L. Trimethoprim was not detected in groundwater or drinking water. In drinking water, Sulfamethoxazole was the only detected antibiotic, with maximum concentrations of 5.6 and 5.2 ng/L, respectively [43].

In the course of another study, active pharmaceutical ingredients were analyzed in wastewater, sewage sludge, sewage sludge compost, and on agricultural land before and after the application of sewage sludge compost. At the beginning of the sewage sludge composting process, Carbamazepine was detected at concentrations of 1600 to 1900 µg/kg DM. In the course of composting, the levels were reduced by more than 80%. Other active pharmaceutical ingredients detected in the sewage sludge (sulfamethoxazole, metoprolol, bezafibrate, diclofenac, and ibuprofen) were degraded during the composting process to such an extent that no active pharmaceutical ingredients (or below the detection limit) were found in the sewage sludge compost. Carbamazepine and Erythromycin were found in soil samples analyzed two months after spreading of the sewage sludge compost. In the case of Carbamazepine, applications of sewage sludge compost were identified as the source for the observed concentration level. In the case of Erythromycin, sewage sludge compost was excluded as the source, because this antibiotic was not detected in sewage sludge compost [44].

Through the expansion of WWTPs to include a fourth treatment stage (e.g., through ozonation, activated carbon, advanced oxidation processes, membrane processes, and ferrate), the input of pharmaceutical residues, which can enter the environment via the municipal drainage system, can be reduced. According to the current state of the art, ozonation and activated carbon boast good broad-spectrum efficacy, applicability, and favorable cost–benefits. Both elimination techniques can achieve a broadband effect and a reduction efficiency of more than 80% [45].

### *3.4. Hormonally Active Agents*

Hormones are excreted by humans as water-soluble glucuronides and sulfates. After treatment in wastewater treatment plants, most glucuronides are dissolved because natural fecal bacteria produce large amounts of glucuronidase [46].

In their study, Albero et al. [46] analyzed naturally occurring and synthetic sex hormones in soils treated with sewage sludge. The natural sex hormones studied included progestagen, two androgens (testosterone and trans-androsterone), and three estrogens (E1, E2, and E3). In addition, four synthetic hormones (MES, Dienestrol, Diethylstilbestrol, and EE2) were included in this study. This showed that the removal of estrogenic compounds in wastewater treatment plants was not by biodegradation, but by transfer from the water phase to the sludge because the compounds tend to be lipophilic. Potential contamination of soil with hormones may occur through the application of sewage sludge to arable land. Further degradation of these compounds in soil was analyzed by means of six soil samples from land where sewage sludge had been applied in an enriched form. Three of the synthetic estrogens were found in one of the six samples analyzed. Trans-androsterone and estrone were the only natural hormones detected at low levels ($\leq$0.4 ng/g).

In addition to direct sewage sludge spreading on arable land, it is also possible to apply sewage sludge compost. In the course of the study by the Federal Environment Agency [47], alkylphenols, nonylphenol ethoxylates, bisphenol, butylated hydroxyanisole, and LAS, as well as phthalates and organocin compounds, were analyzed. A significant decrease of 98% in the levels of hormonally active substances was observed in composted sewage sludge compared to non-composted sewage sludge (dewatered sludge) samples. Even in a dewatered sludge sample, which was stored for about six months, a decrease in concentration (15%) could be observed in some cases.

## **4. Alternative Incineration?**

Currently, about 53% of sewage sludge in Austria is not recycled and is thermally treated in waste incineration plants and cement plants. Thermal treatment of sewage sludge can be carried out by mono-incineration, co-incineration, or alternative processes (pyrolysis). These forms of recycling result in partial reductions in potential organic pollutants and volume. The decisive factor for the thermal utilization of sewage sludge is its calorific value. The calorific value depends on the selected sludge treatment process and the remaining content of water and organic matter [48].

Mono-incineration is generally propagated as a future form of sewage sludge utilization, because it allows for phosphorus recycling as well as for the creation of reliable pollutant sinks in sewage sludge. It has therefore been suggested that between 65% and

85% of municipal sewage sludge should be processed through mono-incineration with subsequent phosphorus recovery [49,50].

Currently, two different approaches to phosphorus recovery are being pursued in Austria [10]. First, decentralized concepts that recover phosphorus directly at WWTPs and simultaneously produce marketable products are desirable. This option has been demanded for WWTPs between 20,000 and 50,000 PE60, provided that a residual phosphate content after recovery of <20 g/kg DM is maintained. Second, centralized concepts that go beyond individual WWTP units to large units of mono-incinerators which accept sewage sludge from the surrounding regions and then provide sewage sludge ash for further large-scale industrial processing are under development. It has been suggested that these concepts should be mandatory for WWTPs over 50,000 PE60 [51]. Most (87%) of the total sewage sludge volume is produced by WWTPs with a PE60 value above 20,000, whereas 72% is produced by WWTPs with a PE60 value above 50,000 (cf. Figure 1).

For mono-incineration, it is essential to consider the waste hierarchy according to the Waste Management Act [52], according to which, recycling is preferable to incineration in any case. Additionally, ecological expediency and technical feasibility must be taken into account. In addition, the resulting additional costs must not be disproportionate compared to other waste treatment processes, and a market for the recovered materials or energy should either already exist or must be created. Furthermore, there must be compliance with the principle of proximity. Accordingly, self-sufficiency in disposal in one of the nearest suitable facilities must be pursued.

In particular, mono-incineration is intended to prevent microplastic pollution [37]. Various studies on micro- and macroplastic inputs into the environment already exist. However, the input of plastic emissions into soils is still largely unexplored [53]. Central mono-incineration plants are not located in the immediate vicinity of WWTPs; therefore, it can be assumed that the transport of sewage sludge by truck to the incineration plant also emits microplastics through tire abrasion.

In order to minimize the transport volume and to increase the calorific value of the sewage sludge for incineration, a drying plant must be installed at the sewage treatment plants. For economic reasons, drying is usually carried out to 60% to 75% dry matter, corresponding to around 70 to 90 $m^3$ of natural gas per ton of pressed sewage sludge. Overall, a clearly negative energy balance can be assumed due to drying and transport [54].

Maier et al. [55] estimated the specific costs of mono-incineration based on three sites in Baden-Württemberg at 80 to 140 EUR/t filter cake and added 70 to 100 EUR/t filter cake for phosphorus recovery from the ash. Additionally, 30 to 40 EUR/t must be added for sewage sludge drying and, depending on the distance, 5 EUR/t (for a total of 150 km) for transport to the incineration plant [53]. This can be offset by the phosphorus sales revenue (minus conditioning, storage, and marketing). Following Hanßen [56] and Maier et al. [55], and assuming that 100% of the phosphorus contained in the ash can be utilized, as well as an average phosphorous price of 0.80 EUR/kg $P_2O_5$ [57], a sales revenue of about 15 EUR/t filter cake can be obtained.

Mono-incineration only targets the nutrient phosphorus. However, a project in Lingen (Germany) only achieved a feasibly recovery rate of around 13%, based on the phosphorus load in the influent. In particular, there were difficulties because the proportion of insoluble phosphorus was too high due to crystal formation [58].

Following mono-incineration, chemicals must be used in the phosphorus recovery process. At present, it is not yet possible to estimate how many chemicals are needed. According to initial experience in Germany, the amount of acid that needs to be added is almost as high as the amount of ash [56]. The incineration residues must either be disposed of in landfill (slag) or underground (filter cake) [59]. Residues following phosphorus recovery are considered hazardous waste, and must therefore be stored underground. Currently, there are no underground landfill sites in Austria.

## 5. Conclusions

High-quality sewage sludge is essential for the nutrient supply. Organic pollutants can be demonstrably degraded in state-of-the-art composting plants. Mono-incineration followed by phosphorus recovery is still in development, but in future, represents an important disposal path for highly contaminated sewage sludge. In addition, a reduction in pollutants in sewage sludge should be considered to achieve high recycling rates. Considering the uneven distribution of phosphate reserves and the scarcity of this resource, quality sewage sludge composting can make a significant contribution to nutrient supply in accordance with the circular economy. By using sewage sludge compost in agriculture, all the main and trace nutrients it contains are recycled. In addition, carbon, which is needed to maintain and build up humus, is stored in the soil.

For sewage sludge compost to be marketed as a product in Austria, it must meet the requirements stipulated by the Compost Directive, which provides limits for heavy metal contents in sewage sludge for composting. To ensure a correct composting process, the sewage sludge content in the compost heap should be approximately 30% (*v/v*), and the compost heap must be turned regularly. Organic pollutants are demonstrably reduced and, in some cases, completely degraded in the case of a state-of-the-art composting process. The level of pollutants is decreasing in sewage sludge suitable for composting; therefore, it can be assumed that high-quality sewage sludge composts will also be available in future.

Plastic loads that enter sewage treatment plants via the wastewater system and subsequently end up in sewage sludge are currently problematic. In the context of this problem area, the mono-incineration of sewage sludge with subsequent phosphorus recovery is currently being discussed. However, phosphorus recovery after mono-incineration has not yet been sufficiently researched and cannot currently be carried out on an economic scale [48].

Nevertheless, mono-incineration plays an important role in sewage sludge disposal. After all, sewage sludge that does not meet the requirements for quality sewage sludge must also be recycled, in which case, thermal recycling processes are a suitable technique. In this case, technical phosphorus recovery under economic conditions would be desirable in order not to lose this important nutrient. For this approach to be formally implemented, an evidence-based evaluation of limit values for sewage sludge is necessary, as were already defined for heavy metals more than 30 years ago.

In addition, reductions in microplastic loads and organic pollutants in sewage sludge should be discussed as an alternative. Currently, processes for the removal of microplastics as well as organic pollutants in wastewater treatment plants are under development. The most suitable process to extend wastewater treatment depends on the WWTPs' local conditions and on the wastewater matrix. These technologies can be adapted to suit the WWTPs' needs, which is why they can usually be well integrated into the existing plants. The costs incurred for targeted trace contaminant control at municipal WWTPs vary widely and are constantly optimized by newly implemented projects [60]. Mitigation measures should also be taken when undesirable pollutants enter the wastewater system. It is important to identify sources of input in order to avoid them or replace them with alternatives [37,39,61].

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